

Plan for a super η factory at Huizhou accelerator complex*

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As an approximate Goldstone boson with zero quantum number and zero standard model charge, the long-lived η meson exhibits the decay processes that offer a unique opportunity to explore physics beyond the standard model and new sources of charge parity violation. Further, they facilitate the testing of the low-energy quantum chromodynamics theory and measurement of the fundamental parameters of light quarks. To pursue these goals, we propose a plan to construct a super η factory at HIAF high-energy terminal or at CiADS after its energy upgrade. The high-intensity proton beam at HIAF enables the production of many η samples, exceeding 10^{13} events per year during the first stage, utilizing multiple layers of thin targets composed of light nuclei. This paper presents the physics goals, the first-version conceptual design of the spectrometer, and preliminary simulation results.

Keywords: High-intensity frontier, Eta meson factory, New physics, Symmetry breaking, Strong interaction, Silicon-pixel detector

I. INTRODUCTION

The high-luminosity frontier presents one approach to new physics [1], as any small deviations from the standard model (SM) predictions in high-precision measurements have implications for new physics beyond the SM. In the next decade, emerging high-intensity proton accelerators will offer a unique opportunity in the exploration for new physics at an unprecedented level. Indications of new physics have been increasingly reported in the literature, for example, the anomalous muon magnetic moment $(g - 2)_\mu$ [2–4], X17 boson from the decay of the excited state of ^8Be [5–7], lepton flavor universality violation in bottom quark decays [8–12], excesses of cosmic positrons and electrons [13–16], narrow γ ray emissions from the galactic bulge [17], and unexplored nature of dark matter [18–22] and dark energy [23–27]. To date, no evidence of new physics has been observed in the high-energy frontier examined using the large hadron collider. Therefore, some researchers have argued that the new physics of the hidden sector is at low energies [28, 29]. However, it is faintly coupled with the SM, making it elusive. For example, the production rates of the light portal particles bridging the hidden and SM sectors are several orders of magnitudes higher at low energies [28]. Moreover, in low-energy, fixed-target experiments, the use of thick targets allows for considerably higher luminosities.

The η meson is of particular interest because it approximates a Goldstone boson arising from spontaneous chiral symmetry breaking and has zero SM charge [30]. Many strong and electromagnetic decay channels of η are forbidden at the leading order; this enhances the rare decay channels of η meson that are sensitive to new physics. Consequently, the η meson serves as an excellent low-energy labo-

ratory for exploring new physics beyond the SM by observing the dark portal particles from η decays [28, 29, 31] or measuring small discrete symmetry breaking such as charge parity (CP) violation and charged lepton flavor violation [32, 33]. A thorough review on the theoretical developments in η and η' decays have recently been reported [32], with regard to high-precision tests of fundamental physics. The latest theoretical models predict four types of portals: vector portal [34–37], scalar portal [38–44], axion-like portal [45–49], and heavy neutral lepton portal [50–52]. Portal particles are particularly significant in theories that seek to bridge the dark and SM sectors. All these light portal particles can be examined by observing the rare decays of η mesons [31, 32]. Symmetry and symmetry breaking form the core of modern physics. Identifying new sources of CP violation is essential for explaining the baryon–antibaryon asymmetry in the universe. Any charged lepton flavor violation is a strong indication of physics beyond the SM model. Several η decay channels facilitate precise testing of these symmetry breakings. Precise measurements of η decay channels are critical in the efforts to elucidate the charge conjugation (C), parity (P), time reversal (T), CP, and charged lepton flavor violations.

In addition to the exploration for new physics, the high-precision study of η decay provides a unique method for testing the quantum chromodynamics (QCD) theory at low energies [53–58], probing the η structure [59–65], precisely measuring the mass difference of light quarks [66–71], and verifying axial anomalies [72–74]. The electromagnetic decay channels associated with virtual and real photons help constrain the η transition form factor with significantly smaller uncertainties [59–64]; this aids the elucidation of the muon anomalous magnetic moment [2–4]. Quark masses are the fundamental parameters of the SM. As regards experimentally constraining light quark masses, the measurement of the isospin-breaking 3π decay channels of η presents a crucial method. High-precision measurements at a super η factory can reduce the uncertainties of QCD parameters significantly. Precise measurements of some rare η decays facilitate the testing of the chiral perturbation theory at high orders [75],

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which is a rigorous and effective theory for strong interactions at low energies.

As η meson decays involve a wide array of physics phenomena, measurements of η decay have been conducted at facilities worldwide. First, the hadronic generation of η from fixed-target experiments, such as the WASA-at-COSY experiment [76–78] and LHCb experiment [79, 80], have been reported. The WASA-at-COSY collaboration entailed the use of the proton beam at COSY and an internal pellet target, and the number of η event yields on the order of 10^8 . Second, the radiative decay of ϕ and J/ψ at the electron-positron colliders have produced considerable numbers of η samples, aided by low background levels. The number of η events from ϕ decay by the KLOE collaboration is on the order of 10^8 [81–84], while the corresponding number from J/ψ decay by the BESIII collaboration is on the order of 10^7 [85–89]. Third, photoproduction experiments provide a clean environment for the production of η mesons, for example, the A2 experiment at MAMI [59, 90, 91] and the JLab Eta Factory (JEF) [32, 92], which exploit the Primakoff effect [93]. JLab has a long history of studying neutral-meson physics via the Primakoff reaction [94, 95]. In the JEF experiment, approximately 10^9 tagged η events will be collected over the years by using the GlueX spectrometer [96, 97]. Owing to the high-performance calorimetry and high-energy incident photons (up to 11 GeV), remarkable background suppression is achieved for the neutral decay channels. The JEF experiment facilitates the precise measurement of the neutral decay channels of η mesons.

To harness the intriguing discovery potential of light dark portal particles and perform rigorous tests of the SM, it is imperative to build a super η factory using high-intensity accelerators to obtain unprecedented η meson samples. To pursue a vast number of η events, the Rare Eta Decays To Observe Physics beyond the standard model (REDTOP) experiment [31] was proposed in the 2021 US Community Study on the Future of Particle Physics using novel detection techniques. In China, a High-Intensity heavy-ion Accelerator Facility (HIAF) is under construction in Huizhou city by Institute of Modern Physics (IMP), Chinese Academy of Sciences (CAS), which is competitive in the beam intensity. Using this near-future infrastructure, we propose a super η factory at the HIAF high-energy terminal. Undoubtedly, the proposed Huizhou η factory will generate many impactful results that will remarkably advance accelerator and detector technologies.

The remainder of this paper is organized as follows. The proposed Huizhou η factory and its physics goals are described in Sec. II. The conceptual design of the spectrometer is presented in Sec. III. Some preliminary simulation results for some golden channels of the experiment are presented in Sec. IV. In Sec. V, a concise summary and future outlooks are provided.

Table 1. List of the main physics goals of Huizhou eta factory.

Physics goals		Decay channel
New physics	Dark photon & X17	$e^+e^-\gamma$
	Dark higgs	$\pi^+\pi^-\pi^0$ $\pi^0e^+e^-$
	Axion-like particle	$\pi^+\pi^-e^+e^-$ $\pi^+\pi^-\gamma\gamma$
	CP violation	$\pi^+\pi^-\pi^0$ $\pi^+\pi^-e^+e^-$
	Lepton flavor violation	$\gamma\mu^+e^- / \text{c.c.}$ $\mu^+e^- / \text{c.c.}$
Precision test of the SM	η transition form factor	$e^+e^-\gamma$ $e^+e^-e^+e^-$ $\pi^+\pi^-\gamma$
	Light quark masses	$\pi^+\pi^-\pi^0$ $\pi^0\pi^0\pi^0$
	Chiral anomaly	$\gamma\gamma$ $\pi^+\pi^-\gamma$
	Beyond SM weak decay	e^+e^-
	Test chiral perturbation theory	$\pi^+\pi^-\gamma\gamma$ $\pi^0\gamma\gamma$

II. HUIZHOU η FACTORY AND ITS GOALS

The HIAF is a major national science infrastructure facility under construction in Huizhou City, Guangdong province, China, in Southern China [98–100]. The construction of the HIAF began in December 2018, and it will be ready for commissioning by the end of 2025. The HIAF is an accelerator complex mainly consisting of a superconducting electron-cyclotron-resonance ion source, continuous-wave superconducting ion linac, booster synchrotron, high-energy fragment separator, and high-precision spectrometer ring. The layout of HIAF is shown in Fig. 1. Many terminals have been designed alongside the accelerator complex for experiments and applications. With high-intensity technology, HIAF not only provides powerful infrastructure for frontier studies in nuclear, high energy-density, and atomic physics but is also an excellent platform for heavy-ion applications in life, material, and space sciences [100]. HIAF will potentially deliver unprecedentedly intense ion beams from hydrogen to uranium with energies up to GeV/u. The maximum energy of the proton beam is 9.3 GeV [98–100]. Using heavy-ion beams, HIAF provides an extraordinary platform for studies of hypernuclei and the phase structure of high-density nuclear matter. Further, given its capability to generate high-energy proton beams, HIAF provides an excellent opportunity to study light hadron physics and to build an η factory.

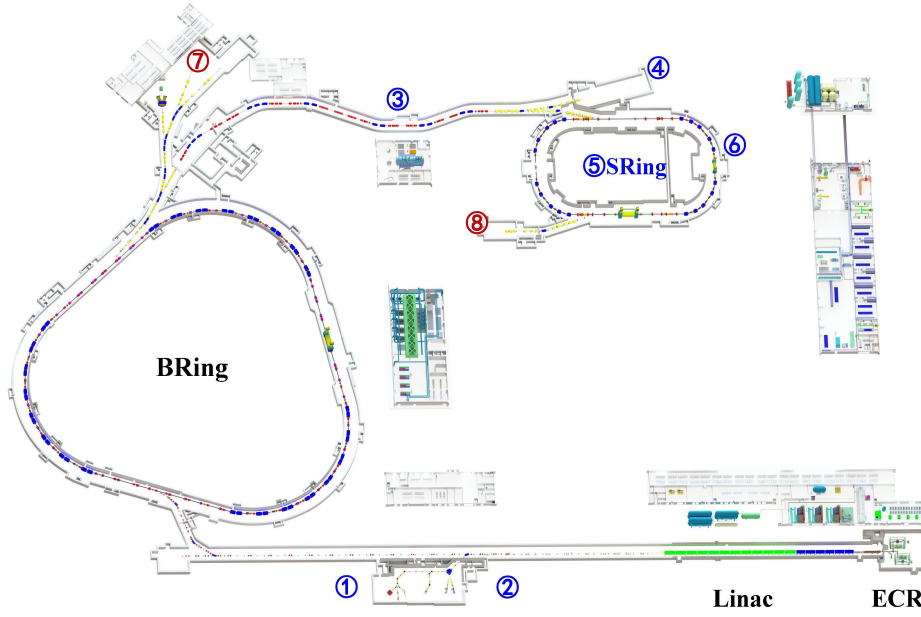


Fig. 1. (Color online) Layout of the HIAF facility. The number “⑦” indicates where the high-energy multidisciplinary terminal is located.

At HIAF, the intensity of the proton beam is higher than 10^{13} ppp (particles per pulse), and the kinematic energy of a proton can reach 9 GeV through the acceleration of the ion linac and booster ring [98–100]. The pulse rate is approximately several Hertz. It is suggested that a super η factory be built at the high-energy multidisciplinary terminal after the booster ring, the terminal “⑦” shown in Fig. 1. The target is made of multiple light-nuclei foils (${}^7\text{Li}$ or ${}^9\text{Be}$) with 1 cm gaps, significantly reducing the coincident background from the same vertex with no simultaneous decrease in the luminosity. Using a proton beam and light nuclear target, the η meson is efficiently produced with a controlled background at HIAF. The beam-energy thresholds are 1.26 GeV and 2.41 GeV for generating η and η' , respectively. Proton-proton scattering at a beam energy of 1.8 GeV results in a large η meson cross-sections [101–104], as indicated by previously reported COSY data (approximately $100\ \mu\text{b}$) [101]. In the case of the nuclear target, the η meson cross-section is even higher. The HIAF beam intensity and a 1 cm-thick lithium target leads to luminosities above $10^{35}\ \text{cm}^{-2}\text{s}^{-1}$ for the Huizhou eta factory experiment. Regardless of the detector and data acquisition system capabilities, the η production rate can be higher than $10^8\ \text{s}^{-1}$ on a light nuclear target ($> 10^{15}$ per year).

The China Initiative Accelerator Driven Sub-critical System (CiADS) is another high-intensity proton accelerator designed for verifying the principle of nuclear waste disposal [105–110]. It provides a remarkably powerful continuous proton beam. The designed full power of the CiADS accelerator is 2.5 MW, with a beam intensity of 3.15×10^{16} pps. CiADS is also appropriate for building a super η factory, provided the energy of CiADS is upgraded to approximately

2 GeV. Because an upgrade to the CiADS accelerator is anticipated to require several years, the HIAF high-energy terminal is deemed more appropriate for the proposed Huizhou η factory.

At the Huizhou η factory, the number of η meson samples is expected to be significant, approximately four orders of magnitude greater than that of the current η events achieved worldwide. With such an enormous yield of η mesons, the main physical goals of the Huizhou η factory would be to discover new physics by searching for new particles and discrete symmetry breaking and to study SM with extremely high precision. New particles of interest emerging from η and η' decays are the predicted light portal particles below the GeV level, which faintly bridges the SM sector with the hidden sector. Examples include the dark vector particles [34–37], dark scalar particles [38–44], and axion-like particles [45–49]. The protophobic X17 boson of the fifth force [5–7] can also be studied via rare η decay. The remarkably large number of η mesons affords a good opportunity to study new sources of CP violation, which is essential for the matter–antimatter asymmetry in the universe, and to search for charged lepton flavor violation, which is a clear and strong indication of new physics. Finally, precise η decay measurements are critical for high-precision study of the SM, such as strictly constraining the light quark mass difference, precise measurement of meson structure, and high-precision testing of chiral perturbation theory. The primary physics interests are listed in Table 1. As the spectrometer at the Huizhou eta factory is particularly suitable for measuring charged particles, the charged decay channels must be attributed a high priority for the proposed experiment, for example, $\eta \rightarrow \pi^+\pi^-\pi^0$, $\eta \rightarrow e^+e^-\gamma$, $\eta \rightarrow \pi^+\pi^-e^+e^-$, and $\eta \rightarrow e^+e^-$.

III. A COMPACT AND LARGE-ACCEPTANCE SPECTROMETER WITH SILICON PIXELS

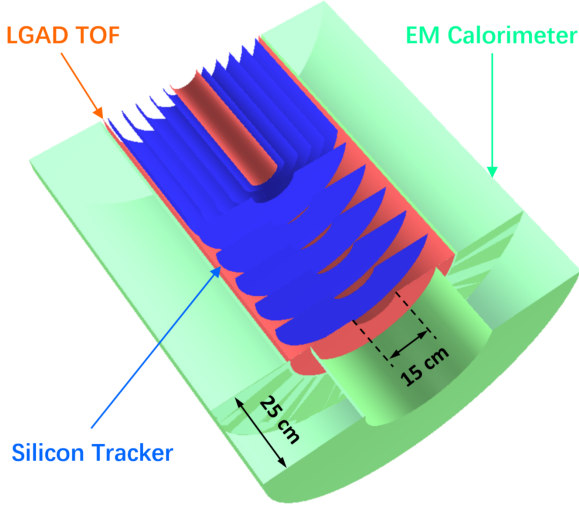


Fig. 2. (Color online) The conceptual design of a compact spectrometer for the η factory. The spectrometer mainly relies on silicon detector technology, with the monolithic silicon pixel tracker and fast LGAD TOF detector of low material budget. The silicon tracker is wrapped with a fast lead-glass calorimeter for high-energy photons.

With the rapid development of monolithic silicon pixel technology [111], we developed the concept of a large acceptance and compact spectrometer with silicon pixels to detect the final-state particles at a high event rate. The current design of the spectrometer comprises four main parts: tracking system for charged particles made of silicon pixels, time-of-flight detector for particle identification made of silicon low-gain avalanche detector (LGAD), electro-magnetic calorimeter (EM calorimeter) for photon measurement made of lead glass [112], and superconducting solenoid. The 3D design of the spectrometer is shown in Fig. 2. Because of the high granularity and low position resolution of the silicon pixel detector, it is a compact spectrometer with a small volume. Therefore, the EM calorimeter and solenoid are of small size, which reduces the cost of spectrometer fabrication. The inner radius of the super-conducting solenoid is approximately 70 cm, and all the main detectors are within the solenoid.

The multi-layer target is placed inside the spectrometer close to the entrance such that there is a large acceptance for fixed-target experiments. Using the current conceptual design of the spectrometer, all forward particles except small-angle particles are covered without dead zones.

To achieve a high-rate capacity for the silicon pixel tracker, the silicon detector group attempted dual measurements of the energy and arrival time of each pixel [113–117]. Using different arrival times, hits from different events can be distinguished. For the first version of the silicon pixel chip ($\sim 1 \text{ cm} \times 1 \text{ cm}$) with approximately 100k pixels, it takes approximately $600 \mu\text{s}$ to read all the pixels in the scan mode,

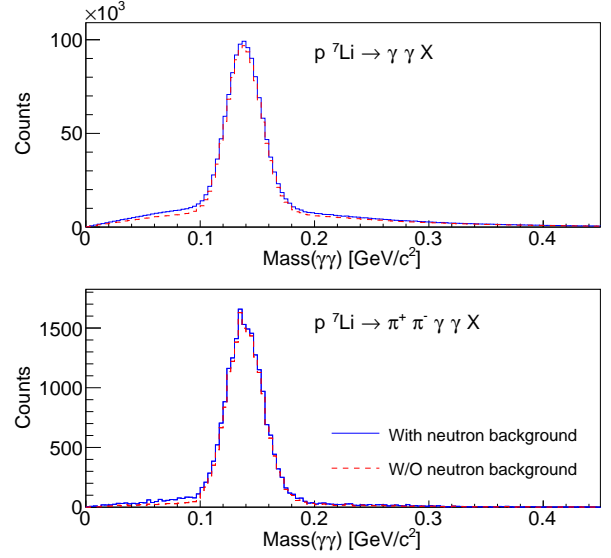


Fig. 3. (Color online) Invariant mass distributions of two γ s from the simulations with and without the neutron contamination. The $p\text{-}^7\text{Li}$ events are generated with the GiBUU package. The γ s are detected under two different scenarios: (1) we assume that the calorimeter cannot distinguish the neutron from the photon (with neutron background); and (2) we assume that the calorimeter can well distinguish the neutron from the photon (without neutron background).

and the resolution of the arrival time is approximately 400 ns. The objectives of future silicon pixel chips are a resolution of 10 ns for arrival time, pixel size of $30 \mu\text{m}$, and scan time of $100 \mu\text{s}$ for approximately 100k pixels. Under the particle multiplicity of the Huizhou eta factory and with the pixel chip more than 5 cm away from the interaction point, the designed silicon pixel chip can easily record events at a rate greater than 100 MHz.

In the current conceptual design of the spectrometer, the calorimeter material is lead glass, which generates only prompt Cherenkov photons. Therefore, it has good time resolution around 100 ps for particle detection. Simultaneously, lead glass is not sensitive to the hadronic shower initiated by nucleons and pions, which means that it has low efficiency for the neutron background and offers additional hadron background suppression capability. Our Geant4 simulation [118–120] discovered that low-energy neutrons ($E_k < 0.3 \text{ GeV}$) generate almost no hits in the lead glass calorimeter, and a high-energy neutron ($E_k > 1 \text{ GeV}$) has only approximately 45% probability of depositing more than 10 MeV energy in the calorimeter. As most neutrons from $pA \rightarrow X$ collision are low-energy neutrons, the neutron background in photon measurements can be eliminated effectively with the lead glass calorimeter. For inelastic events generated with the GiBUU package [121–124], Fig. 3 shows the invariant mass distributions of two photons, with and without the neutron background. The background of the π^0 signal due to neutron contamination is negligible, especially for the channel $p\text{-}^7\text{Li} \rightarrow \pi^+ \pi^- \pi^0 X$. In the simulation, the threshold for a hit

in the calorimeter corresponds to the signal generated by a 50 MeV photon. Neutrons deposit less energy in the calorimeter than photons, and with the same amount of energy deposition, the hadronic shower initiated by the neutron generates fewer Cherenkov photons. Therefore, the abundant neutron background at low energy is strongly suppressed in the measurement of photons and π^0 .

Although a lead glass calorimeter is effective at suppressing hadron backgrounds and is cost-effective, it has significant drawbacks compared to conventional crystal calorimeters. First, the low Cherenkov light yield and severe light attenuation of lead glass result in poor energy resolution. Lead fluoride crystals, which exhibit less light attenuation, can be used instead, but they are much more expensive. Another disadvantage is poor radiation resistance. Although radiation-resistant lead glass can be used to improve this, it suffers from worse light attenuation. Additionally, due to the low light yield, the Cherenkov light being mainly in the UV range, and the detector being in a magnetic field, large-sized UV-sensitive SiPMs are required. These drawbacks present challenges for the use of lead glass in this project.

One option is to use the ADRIANO2 [125] dual-readout calorimeter currently being developed by the REDTOP group. This design combines scintillation materials and lead glass to capture both Cherenkov light and scintillation light signals. It employs longitudinal layering and a readout to provide excellent energy resolution and additional capability for low-energy particle identification. This design addresses the shortcomings of using lead glass only.

By applying a full-silicon tracker with small pixel size, the momenta of charged particles are precisely measured with a high event rate, and the sizes of all detectors scale down depending on the size of the inner tracker. This is a compact spectrometer with a large acceptance for fixed-target experiments and competitive functions. The LGAD detector for time-of-flight measurement has a low time resolution and extremely low material budget. The lead glass calorimeter is effective in reducing the neutron background, but its energy resolution is poor. We also look for new EM calorimeter technologies capable of working in a high event rate environment. Therefore, using the current spectrometer design for the Huizhou eta factory, we focus more on the charged decay channels of η mesons. The radiation dose for the spectrometer was simulated using both Geant4 [118–120] and FLUKA [126–128]. Under the condition of a 100 MHz inelastic scattering rate, over a one-month data acquisition period, the innermost LGAD is expected to experience a maximum 1 MeV neutron equivalent fluence of $3 \times 10^{12} n_{\text{eq}}/\text{cm}^2$ and a maximum dose of 200 Gy. Meanwhile, the lead glass of EM calorimeter is expected to experience a maximum 1 MeV neutron equivalent fluence of $5 \times 10^{11} n_{\text{eq}}/\text{cm}^2$ and maximum dose of 100 Gy. Thus, these subsystems can survive for several years before significant radiation damage occurs.

IV. PRELIMINARY RESULTS OF SIMULATIONS

To determine the physics impact and feasibility of the experiment, we performed simulations of some golden channels for the Huizhou eta factory project. The simulation study is the first step for us to acquire the details regarding the resolutions, efficiency of the signal channel, background distribution, precision of the planned measurement, and/or sensitivity to new physics.

For the background events in p-A collisions, we used the GiBUU event generator [121–124] to perform the simulation. GiBUU is suitable for proton-induced nuclear reactions from low to intermediate energies, with final-state interactions being handled well [121]. The GiBUU event generator is based on the dynamic evolution of a colliding nucleus-nucleus system within the relativistic Boltzmann-Uehling-Uhlenbeck framework, which considers the hadronic potentials, equation of state of nuclear matter, and collision terms. In GiBUU, low-energy collision is dominated by resonance processes, while high-energy collision is described by a string fragmentation model implemented in Pythia. For η production, $N^*(1720)$ in the process $NN \rightarrow NR$ plays a dominant role [129]. Thus, the GiBUU event generator perfectly covers the kinematical regions of the HIAF and CiADS accelerator facilities.

In our simulation, the kinematic energy of the proton beam was 1.8 GeV, which is slightly below the ρ meson production threshold to lower the background. Using the lithium target, we found that the number of neutrons is approximately 1000 times the number of η mesons, and the number of π^0 mesons is approximately 50 times that of η mesons. We further coded the decay chains of π^0 and η . For signal event generation of dark portal particles, we constructed a simple event generator for the channels of interest. We also used another BUU generator [130] and the Urqmd package [131–133] to estimate the η production cross-section. The η production probability was 0.76% for inelastic collisions.

To quantify the detection efficiency and resolutions, we developed a detector simulation package ChnsRoot, which is based on the FairRoot framework [134, 135]. Currently, we have a reliable, fast simulation tool based on parameterizations validated by Geant4 simulations. The innermost and outer-most radii of the silicon pixel tracker are 7.5 cm and 27.5 cm, respectively. The magnetic field strength is 0.8 Tesla. The energy resolution of the calorimeter is $\delta(E)/E = \sqrt{a^2 + b^2/(E/\text{GeV})}$ for photons, with $a = 0.028$ and $b = 0.056$ estimated using Geant4. The neutron efficiency of the calorimeter as a function of energy and scattering angle was also studied in detail with Geant4. Calorimetric responses to different types of particles were carefully studied to achieve a realistic fast spectrometer simulation.

To understand the physics impact of the measurement, the statistics of the produced η samples was the most important input for the simulation. To be conservative in our experimental projections, in this simulation, we considered a prior experiment with only one month of operation. Based on the evaluated luminosity and p-A cross section, the potential production rate of η can exceed 10^8 s^{-1} , at an inelastic event

rate of approximately 10^{10} s^{-1} . A silicon pixel detector with a high granularity can operate at a high event rate ($> 100 \text{ MHz}$) without a significant pile-up of events. However, considering the radiation hardness of the detector, and limits of the current data acquisition (DAQ) system, we make a notably conservative estimate of the event rate for the Huizhou η factory experiment. The event rate of inelastic scattering is assumed to be 100 MHz , and the η production rate is approximately 760 KHz . We also assumed a conservative duty factor for the accelerator of which is 30% . Using these settings, the number of η mesons produced is 5.9×10^{11} for the first experiment with only onemonth of running time. Thus, in the following simulations, we assume that only 5.9×10^{11} eta mesons were produced in the previous experiment.

The statistics of η meson samples can be increased to magnitudes higher, as the experiment will run for years. The event rate can also be increased with improvements in the detector radiation hardness and speed of DAQ system, and the proton beam can be delivered to the high-energy terminal with a high duty factor.

A. Dark photon search

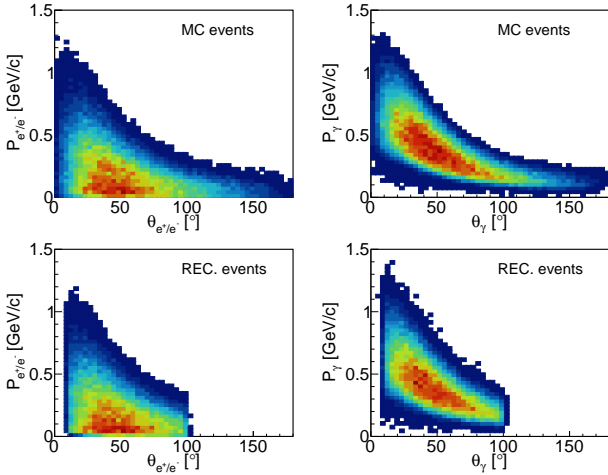


Fig. 4. (Color online) Momentum v.s. angle distributions of the final-state particles of $\eta \rightarrow e^+e^-\gamma$ decay channel. The top pads show the kinematic distributions of the final states from the event generator, while the bottom pads show the kinematic distributions of the reconstructed particles from the fast detector simulation. The designed spectrometer covers the main and large kinematic region of the final-state particles.

The decay channel $\eta \rightarrow e^+e^-\gamma$ is particularly interesting because this channel is relevant to the search for the dark photon [34–37] and light protophobic X17 boson [5–7], which decay into an electron-positron pair. Simultaneously, from the precise measurement of this channel, we can precisely extract the transition form factor of η , which is an important input for the theoretical calculation of muon anomalous moment $(g - 2)_\mu$. The dark photon is the most popular type

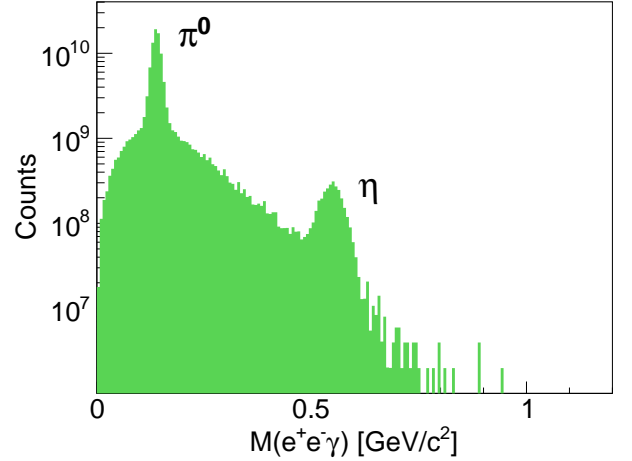


Fig. 5. (Color online) Invariant mass distribution of $e^+e^-\gamma$ from the simulation data for one-month running of Huizhou η factory experiment.

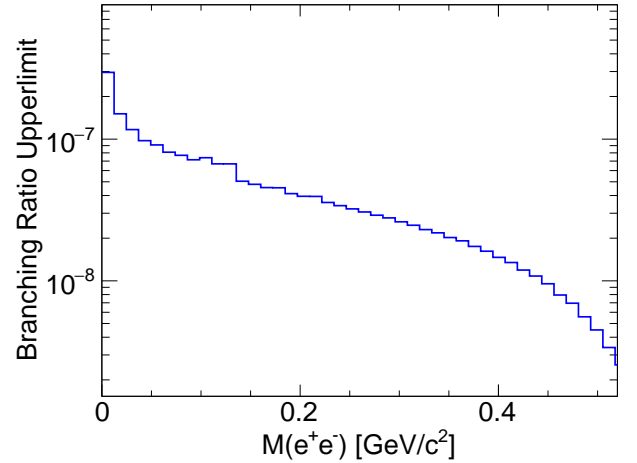


Fig. 6. (Color online) Estimated branching-ratio upper limit of dark photon for one-month running of Huizhou η factory experiment, under a conservative event rate of 100 MHz of inelastic reactions.

of dark portal particle, and it feebly connects the SM model sector with the possible hidden sector. Here, we focus on the physics impact on the dark photon from the simulation data of the Huizhou eta factory experiment.

Figure 4 shows the kinematic distributions of the final-state particles of channel $e^+e^-\gamma$, from the event generator and particle reconstruction in the spectrometer simulation. Evidently, most of the final electrons have a low momentum ($< 0.5 \text{ GeV}/c$) and go to angles from 10° to 100° . The average energy of the final photon is approximately 0.4 GeV , and the photons have similar electron-scattering angles. The designed spectrometer covers most of the electrons and photons, and the overall efficiency of the channel is estimated to be 60% using the simulation. Low-energy electrons can be identified effectively using energy decomposition dE/dx measured by

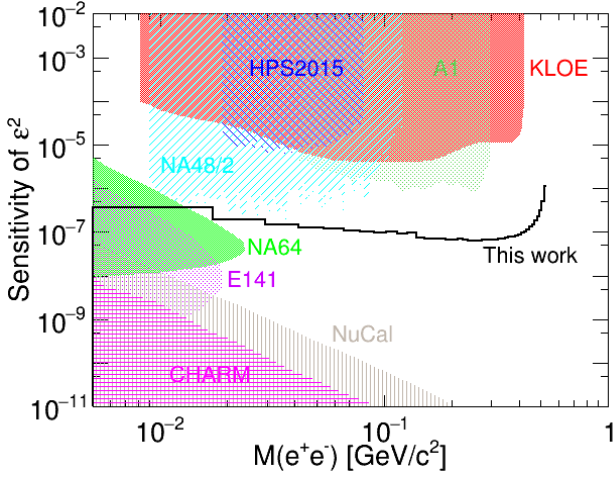


Fig. 7. (Color online) Estimated ϵ^2 sensitivity of dark photon for one-month running of Huizhou η factory experiment, under a conservative event rate of 100 MHz of inelastic reactions. The shaded exclusion areas in the figure correspond to previous experiments (HPS2015, A1@MAMI, KLOE, NA48/2, NA64, E141, NuCal, and CHARM) are taken from Refs. [136–144].

a silicon pixel tracker. A high-energy electron can be identified using the calorimeter, as the pion initiates few Cherenkov photons in the lead glass calorimeter.

The distribution of the reconstructed invariant mass of $e^+e^-\gamma$ is shown in Fig. 5. Clearly, the peaks of π^0 and η have a low background underneath. Owing to suppression of the bremsstrahlung radiations in the proton scattering process, the electron and photon backgrounds are not significant. η samples with a high purity can be selected by performing a cut on the invariant mass of $e^+e^-\gamma$. In this simulation, the invariant mass must be within the range of $[m_\eta - 3\sigma, m_\eta + 3\sigma]$.

To estimate the sensitivity of the proposed experiment to the dark photon, we carefully studied the background distribution through the simulation. The background events are generated using GiBUU with some decay chains added by us. In the simulation data, there is no bump in the invariant mass distribution of electrons and positrons. We assume that there is no dark photon in the simulation and the invariant mass distribution of e^+e^- is the pure background distribution. No observation of the dark photon means that the statistical significance of the dark photon peak is less than 3σ . Consequently, we get a formula for the branching-ratio (BR) upper limit of the dark photon channel as follows:

$$\text{BR}^{\text{up}} = \frac{3 \times \sqrt{N_{\text{bg}} \times \epsilon_{\text{bg}}}}{N_\eta \times \epsilon_{\text{sig}}}, \quad (1)$$

where N_{bg} is the number of background events, ϵ_{bg} is efficiency for the background event, N_η is the total number of eta mesons produced in the experiment, and ϵ_{sig} is the efficiency of the dark photon channel. $N_{\text{bg}} \times \epsilon_{\text{bg}}$ is actually the number of background events survived after all event selections. Based on the simulation of a one-month experiment of the Huizhou eta factory, the BR upper limit of dark photon in

η decay was evaluated and is shown in Fig. 6. The sensitivity of the kinematic mixing parameter ϵ^2 is closely related to the upper limit of the branching ratio, which is expressed as

$$S(\epsilon^2) = \frac{\text{BR}^{\text{up}}}{2|F(m_A^2)|^2 \left(1 - \frac{m_A^2}{m_\eta^2}\right)^3}, \quad (2)$$

where m_A and m_η are the masses of the dark photon and η meson, respectively, and F denotes the transition form factor of η . The final ϵ^2 sensitivity of the one-month experiment to the dark photon is shown in Fig. 7. Our simulation indicates significant sensitivity to ϵ^2 below 10^{-7} , which surpasses the precision of previous experimental measurements (HPS2015 [136], A1@MAMI [137], KLOE [138], NA48/2 [139], NA64 [140], E141 [141], NuCal [142, 143] and CHARM [144]). The proposed experiment will be a valuable complement to other dark photon searches. After years of running of the experiment, the parameter space below the η mass will be almost ruled out when the results are considered in conjunction with the findings of many other experiments worldwide [136, 137, 142–150].

B. Light dark Higgs search

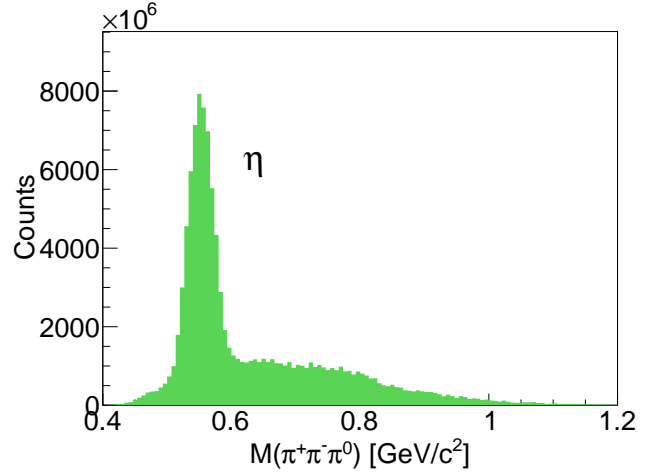


Fig. 8. (Color online) Invariant mass distribution of $\pi^+\pi^-\pi^0$ from the simulation data for one-month running of Huizhou η factory experiment.

The light dark Higgs [38–44] is another representative dark portal particle, which couples the hidden scalar field with the Higgs doublet. Thus, the dark Higgs is weakly connected to leptons and quarks via the Yukawa coupling. Therefore, the dark Higgs can be produced in the hadronic process and can decay into lepton and quark pairs. In a hadrophilic scalar model, the dark Higgs mainly couples to the up quark; thus, it predominantly decays into pions. At the Huizhou eta factory, we could search for the dark Higgs in the following channels: $\eta \rightarrow \pi^0 h \rightarrow \pi^0 e^+ e^-$ and $\eta \rightarrow \pi^0 h \rightarrow \pi^0 \pi^+ \pi^-$. In these η

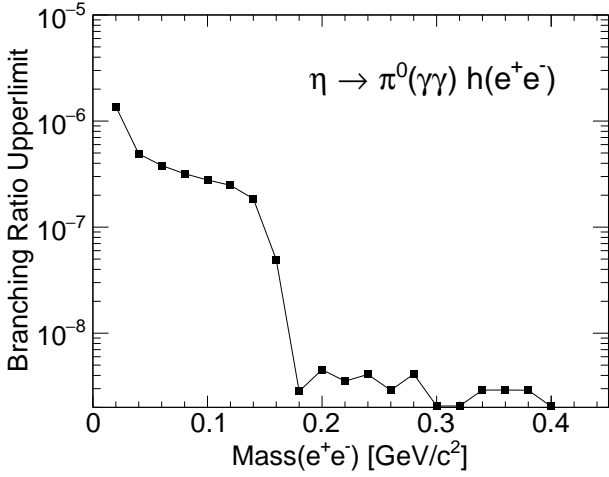


Fig. 9. (Color online) Estimated branching-ratio upper limit of light dark Higgs particle from $\pi^0 e^+ e^-$ channel for one-month running of Huizhou η factory experiment, under a conservative event rate of 100 MHz of inelastic reactions. The invariant mass of $\pi^0 e^+ e^-$ is required to be in the η mass region.

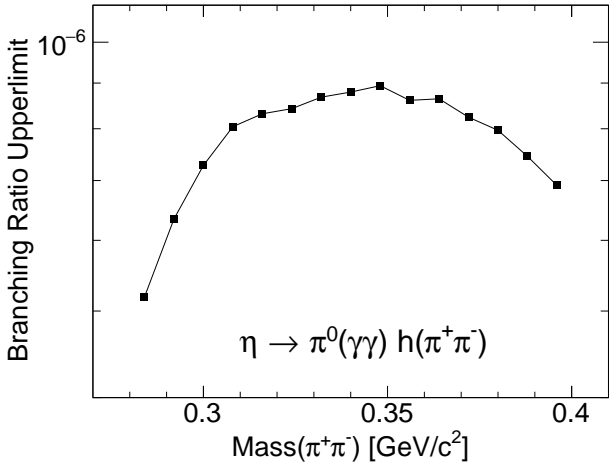


Fig. 10. (Color online) Estimated branching-ratio upper limit of light dark Higgs particle from $\pi^0 \pi^+ \pi^-$ channel for one-month running of Huizhou η factory experiment, under a conservative event rate of 100 MHz of inelastic reactions. The invariant mass of $\pi^0 \pi^+ \pi^-$ is required to be in the η mass region.

rare decay channels, a bump in the invariant mass distribution of $e^+ e^-$ or $\pi^+ \pi^-$ is a clear signal of the possible dark scalar particle.

The distribution of reconstructed invariant mass of $\pi^+ \pi^- \pi^0$ is shown in Fig. 8. The peak of η meson with a low background underneath is evident. In the GiBUU simulation, the background from the direct multi-pion production is low compared to the η production because the incident energy of the proton is low (1.8 GeV). η samples from $\pi^+ \pi^- \pi^0$ can be selected with a high purity by performing a cut on the invariant mass of $\pi^+ \pi^- \pi^0$ in the range of $[m_\eta - 3\sigma, m_\eta + 3\sigma]$.

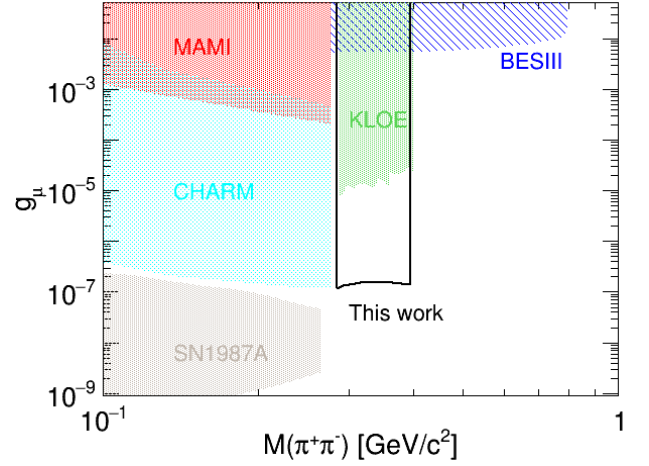


Fig. 11. (Color online) Estimated g_u sensitivity of light dark Higgs particle in a hadrophilic scalar model [40, 41], for one-month running of Huizhou η factory experiment, under a conservative event rate of 100 MHz of inelastic reactions. The previous experimental data for the shaded exclusion areas (BESIII, KLOE, MAMI, CHARM, and SN1987A) in the figure are taken from Refs. [40, 83, 151–154].

The low background does not hinder our explorations much for the rare decays of η meson.

From the simulation, the efficiencies of the $\pi^0 e^+ e^-$ and $\pi^0 \pi^+ \pi^-$ channels are all above 40% with the conceptual design of the spectrometer. The resolutions for the invariant masses of $e^+ e^-$ and $\pi^+ \pi^-$ are 2 MeV/ c^2 and 1 MeV/ c^2 , respectively. In this study, the bin width for the invariant mass was six times greater than the resolution. The background distributions without the dark Higgs particle are simulated using the GiBUU event generator, and the total number of inelastic scattering events scales up to 5.9×10^{11} . Because there is no dark Higgs observed in our simulation data, the upper limit of the branching ratio of the dark Higgs particle is given by the formula in Eq. (1). The BR upper limits of the light dark Higgs particle in $\pi^0 e^+ e^-$ and $\pi^0 \pi^+ \pi^-$ channels are shown in Fig. 9 and Fig. 10, respectively, as a function of the mass of the dark Higgs.

As evident from Fig. 10, the BR upper limit of dark Higgs in the $\eta \rightarrow \pi^0 \pi^+ \pi^-$ channel lies between 10^{-6} and 10^{-7} for one-month running of the experiment. As shown in Fig. 9, the upper limit in the $\pi^0 e^+ e^-$ channel is below 10^{-8} in most ranges of the dark Higgs mass. This is mainly due to the lower electron background in p – A collisions, compared to the strong pion background. Moreover, the upper limit in the $e^+ e^-$ channel decreases quickly, reaching a value below 10^{-8} when the mass exceeds 0.14 GeV. This is because most of the $e^+ e^-$ background originates from π^0 decay. Therefore, the $e^+ e^-$ channel offers the advantage of searching the dark Higgs with a higher mass than the pion. With years running of the Huizhou eta factory experiment, we are confident that the accumulated data will provide strong constraints on the possible dark Higgs particle.

Under the hadrophilic scalar model [40, 41], the sensitivity to the parameter g_u (coupling of the dark scalar to the first-generation quark) is computed and shown in Fig. 11, compared with the constraints provided by previous experimental data (BESIII [151], KLOE [83], MAMI [152], CHARM [153, 154], and SN1987A [40]). The g_u sensitivity from one-month running of the proposed Huizhou η factory will exceed the current experimental limits in the accessed mass range. The proposed super η factory will play an important role in the search for light dark scalar portal particles.

C. C and CP violation in $\eta \rightarrow \pi^+\pi^-\pi^0$

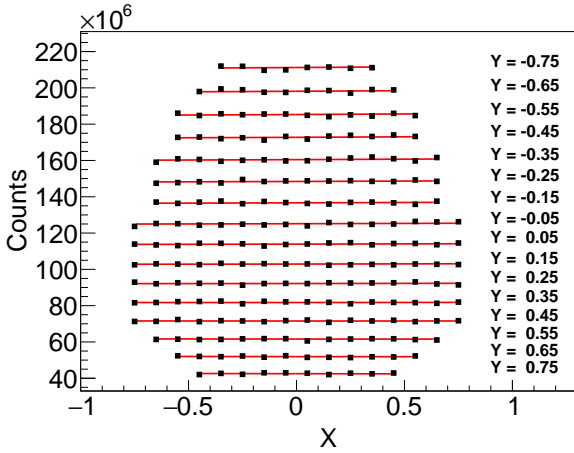


Fig. 12. (Color online) Event distributions of $\eta \rightarrow \pi^+\pi^-\pi^0$ decay channel (black squares) in different X and Y bins for one-month running of Huizhou η factory experiment, under a conservative event rate of 100 MHz of inelastic reactions. The Dalitz distribution of $\eta \rightarrow \pi^+\pi^-\pi^0$ is fitted with a simple model (red lines). See the main text for more explanations.

The CP violation in the flavor-nondiagonal process owing to the Cabibbo—Kobayashi—Maskawa (CKM) matrix phase is insufficient to explain the matter-antimatter asymmetry in the universe. Therefore, the search for new sources and flavor-diagonal CP violation has become popular in the field of high-energy physics. The $\pi^+\pi^-\pi^0$ decay channel of the η meson is of particular interests, as it provides a unique process to probe the flavor-diagonal C and CP violation beyond the SM. This type of CP violation is not constrained by measurement of the nucleon electro-dipole moment (EDM). Thus, high-precision experimental studies have been lacking in this regard [33]. Because of the interference between the C-conserving and C-violating amplitudes, the CP violation signal can be large. Small C and CP violations can be detected from a precise measurement of the mirror symmetry in the Dalitz decay plot of the $\pi^+\pi^-\pi^0$ channel.

The direct observable of the charge asymmetry and CP violation is mirror symmetry breaking in the Dalitz plot of $\eta \rightarrow \pi^+\pi^-\pi^0$, that is, asymmetry under the exchange of u and t

($u \equiv (p_{\pi^+} + p_{\pi^0})^2$, $t \equiv (p_{\pi^-} + p_{\pi^0})^2$, and $s \equiv (p_{\pi^+} + p_{\pi^-})^2$). The C and CP violation is reflected in the asymmetry of the decay events of $u > t$ and $u < t$. Typically, mirror asymmetry is vividly illustrated in the Dalitz plot of X and Y variables, which are defined as

$$X \equiv \sqrt{3} \frac{T_{\pi^+} - T_{\pi^-}}{Q_\eta} = \frac{\sqrt{3}}{2m_\eta Q_\eta} (u - t), \quad (3)$$

$$Y \equiv \frac{3T_{\pi^0}}{Q_\eta} - 1 = \frac{3}{2m_\eta Q_\eta} [(m_\eta - m_{\pi^0})^2 - s] - 1,$$

where $Q_\eta = m_\eta - m_{\pi^+} - m_{\pi^-} - m_{\pi^0}$ and T_{π^i} are the total kinematic energy and kinematic energy of π^i in the η rest frame, respectively. The distribution asymmetry across $X = 0$ is an observable of the new type of CP violation. The Dalitz distribution of the decay probability can be conveniently parameterized as a polynomial expansion expressed as

$$N(X, Y) = N_0(1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + hXY^2 + lX^3 + \dots), \quad (4)$$

where a, b, c, \dots are free parameters. The nonzero values of the parameters c, e, h , or l are a strong indication for the flavor-diagonal C and CP violation.

The $\pi^+\pi^-\pi^0$ channel is a major decay channel of the η meson, and we can obtain a huge number of decay events from the Huizhou eta factory experiment. From the simulation, the efficiency for the 3 pion channel is estimated to be approximately 45%. The event distributions in the different X and Y bins are shown in Fig. 12 for one-month running of the experiment. The statistical error bars are too small to display in the figure. We performed a model fit to the data using Eq. (4). The uncertainty of the parameter c is approximately 5×10^{-5} , which is two orders of magnitude smaller than those of the current analyses of COSY and KLOE-II data [77, 83]. Over the years running the project, the C and CP violation can be tested at a satisfactory level of precision.

D. Low-background η data from exclusive channel $\text{pd} \rightarrow \eta^3\text{He}$

Here, we emphasize that low-background data of η mesons can be obtained at the Huizhou eta factory via the ^3He tagged events of the reaction $\text{pd} \rightarrow \eta^3\text{He}$. In addition to the exclusivity of the measurement, the momentum and angle of the final-state particle are highly correlated in the two-body-to-two-body scattering process. By tagging ^3He and cutting the momentum-angle correlation, the background is significantly reduced. The cross-section of the $\text{pd} \rightarrow \eta^3\text{He}$ reaction is not small [101, 155–159]; it is $0.4 \mu\text{b}$ and near the production threshold measured by the COSY-ANKE collaboration [157]. The multiplicity of the final particles using deuterium target is much smaller than that using other nuclear targets. Therefore, the event rate for $\text{pd} \rightarrow \eta^3\text{He}$ measurement can be set at a much higher rate to increase the amount of low-background data.

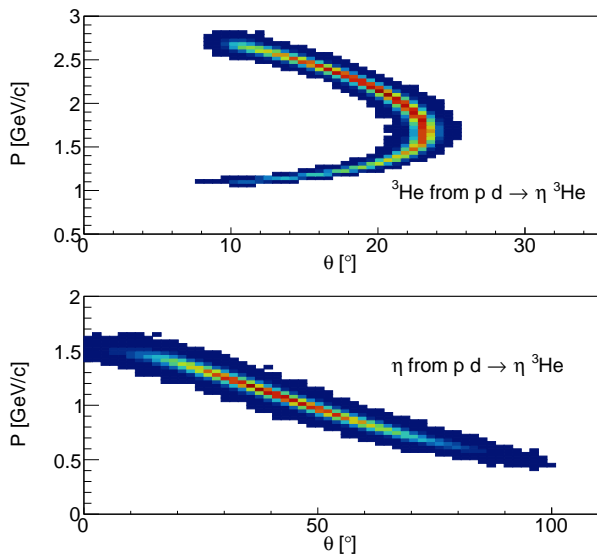


Fig. 13. (Color online) Kinematic distributions of the reconstructed ${}^3\text{He}$ and η from a fast simulation of the spectrometer. The scattering angle and momentum are highly correlated for the particles in the reaction $pd \rightarrow \eta {}^3\text{He}$. The angular and momentum resolutions are small from the silicon pixel tracker.

Fig. 13 shows the two-dimensional kinematic distributions of ${}^3\text{He}$ and η in the momentum vs. angle plane. Evidently, the final ${}^3\text{He}$ mainly goes to the region of scattering angle from 15° to 25° , whereas the η meson has a scattering angle mainly in the range from 20° to 70° . The conceptual design of the spectrometer is suitable for tagging ${}^3\text{He}$ and collecting the decay particles of the η meson with high acceptance. As evident from Fig. 13, the momentum and angular resolutions of the silicon pixel tracker are excellent for selecting exclusive events of $pd \rightarrow \eta {}^3\text{He}$.

In short, using the high-intensity proton beam and deuterium target, we can measure with both high luminosity and precision at the Huizhou eta factory. These high-statistic and low-background data are valuable in the search for new light particles, looking for the violations of CP and other discrete symmetries, measuring the transition form factor and $u - d$ quark mass difference, and testing the low-energy effective theory of the strong interaction. The systematic uncertainty from the background can be well controlled with the tagged η data of $pd \rightarrow \eta {}^3\text{He}$.

V. SUMMARY AND OUTLOOK

A super η factory at Huizhou is proposed for pursuing a variety of meaningful and challenging physical goals. HIAF accelerator complex and conceptual design of the spectrometer

are briefly discussed. More than 10^{13} η mesons can be produced with 100% duty factor of the accelerator. The performance of the spectrometer is studied with Geant4 simulation, demonstrating satisfactory efficiency and resolution. The designed spectrometer is particularly useful for the detection of charged particles and exhibits the radiation hardness required for high-luminosity experiments.

Through simulations, some key channels of the Huizhou η factory experiment are investigated. The preliminary results from the fast simulation show that the Huizhou η factory will play a crucial role in searching for the predicted light dark portal particles and new sources of CP violation. The proposed experiment has the potential to significantly constrain the parameter space of the dark photon in the low-mass region together with other experiments. The sensitivity to light dark scalar particle is estimated to be at an unprecedented level. The C and CP violation in the channel $\eta \rightarrow \pi^+ \pi^- \pi^0$ can be measured at least two orders of magnitude more precisely than up-to-date measurements worldwide. Based on the simulation, the conceptual design of the spectrometer is capable of measuring the tagged η events of the reaction $pd \rightarrow \eta {}^3\text{He}$. The tagging ${}^3\text{He}$ method provides a measurement of both high statistics and low background, which is vital for the precise study of η physics.

After completing the planned accumulation of η decay samples, we could increase the beam energy and produce the η' meson. The physical goals of high-precision studies of η' meson decay closely resemble those of the η meson. An advantage of studying η' decay is the ability to explore dark portal particles over a wider mass range, given that the η' meson is heavier than the η meson. High-precision studies could also be conducted using the same spectrometer on η' and ϕ meson decays, thereby boosting the discovery potential of the proposed Huizhou η factory project.

To further improve the discovery potential of the spectrometer, it is essential to enhance its capacity to detect neutral particles. The current lead glass EM calorimeter exhibits standard energy resolution; therefore, new calorimeter technologies with fast response times (< 100 ps) and low energy resolution ($< 3.5\%$ at 1 GeV) is imperative. With the rapid development of silicon photomultipliers and electronics, dual-readout calorimetry for collecting scintillation and Cherenkov photons is a viable option for updating the EM calorimeter. The scintillation material significantly improves the energy resolution, while the Cherenkov light provides a sharp time resolution. The particle identification ability can also be enhanced using the dual-readout calorimeter by comparing scintillation and Cherenkov signal amplitudes. Future developments in silicon pixel detectors and electronics will benefit the proposed Huizhou η factory project, enabling improvements in radiation hardness and resolutions, which increase the event-rate limit for the planned high-luminosity experiments.

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